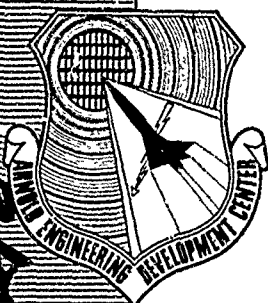


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A COMPARISON OF TRANSITION REYNOLDS NUMBERS FROM 12-IN. AND 40-IN. SUPERSONIC TUNNELS

By

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von Kármán Gas Dynamics Facility
ARO, Inc.

TECHNICAL DOCUMENTARY REPORT NO. AEDC-TDR-63-57

March 1963

AFSC Program Area 750A, Project 8952, Task 895202

(Prepared under Contract No. AF 40(600)-1000 by ARO, Inc.,
contract operator of AEDC, Arnold Air Force Station, Tenn.)

ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

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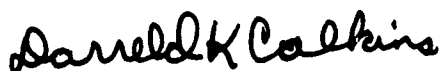
ARO Project No. VT2116

ABSTRACT

Transition Reynolds number measurements on a hollow cylinder in the von Kármán Gas Dynamics Facility's 12-in. and 40-in. supersonic tunnels show that the highest transition Reynolds numbers were obtained in the 40-in. tunnel although the variations with unit Reynolds number were the same at Mach numbers 3 to 5. The influence of nose bluntness in the 40-in. tunnel corresponds closely with the results obtained in the 12-in. tunnel.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.



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NOMENCLATURE

A_S	Stilling chamber area, ft^2
A_t	Throat area, ft^2
a_o	Speed of sound in the stilling chamber, ft/sec
b	Leading edge thickness, in.
M_∞	Free-stream Mach number
p_a	Atmospheric pressure, psfa
p_o	Stilling chamber pressure, psfa or psia
p_r	Reservoir pressure, psia
Δp	Root mean square pressure fluctuation, psia
q_o	Stilling chamber dynamic pressure, psia
Re	Unit Reynolds number, $(U/\nu)_\infty$
Re_b	Bluntness Reynolds number, $(U/\nu)_\infty b$
Re_t	Transition Reynolds number, $(U/\nu)_\infty X_t$
U	Velocity, ft/sec
W	Sound power output, kilowatt/ ft^2
X_t	Location of boundary-layer transition, in.
λ	Ratio of reservoir to stilling chamber pressure
μ	Dynamic viscosity of air, $\text{lb-sec}/\text{ft}^2$
ν	Kinematic viscosity, μ / ρ , ft^2/sec
ρ	Mass density, $\text{lb-sec}^2/\text{ft}^4$
ρ_a	Atmospheric density, $\text{lb-sec}^2/\text{ft}^4$

1.0 INTRODUCTION

Tests of the AGARD calibration models have been conducted in many of the tunnels at the von Kármán Gas Dynamics Facility (VKF), Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), U. S. Air Force. In some cases the same model has been tested in different tunnels in an effort to establish comparisons and to detect differences which are inherent with the tunnel rather than the model or instrumentation system. Force tests of AGARD calibration Model A were conducted in the 12-Inch Supersonic Tunnel (E-1) and the 40-Inch Supersonic Tunnel (A) by Schueler (Ref. 1) to determine the influence of a change in the stilling chamber of the 12-in. tunnel and to compare results (primarily drag) from both tunnels using the same model and instrumentation. It was well established in these tests, from schlieren observations and drag and base pressure measurements, that transition Reynolds numbers were higher in the 40-in. tunnel.

The tests reported herein were conducted in the 40-in. tunnel on a hollow cylinder model, tested previously in the 12-in. tunnel by Potter and Whitfield (Ref. 2), to determine the influence of Mach number, unit Reynolds number, and nose bluntness without introducing additional variables sometimes attendant with the use of different models and instrumentation.

2.0 EXPERIMENTAL APPARATUS

2.1 WIND TUNNEL

Earlier tests on a 3-in. hollow cylinder model reported by Potter and Whitfield (Ref. 2) were conducted in the 12-Inch Supersonic Tunnel (E-1) shown in Fig. 1. This tunnel is an intermittent, variable density, supersonic tunnel equipped with a flexible plate nozzle which provides a Mach number variation from 1.5 to 5. Stagnation pressures from sub-atmospheric to a maximum of four atmospheres are automatically regulated by throttling airflow from an air supply storage system (5,300 ft³) maintained at 150°F and pressures up to a maximum of 4,000 psia; variations in pressure provide a Reynolds number range from 0.3×10^6 to 19×10^6 per ft at $M_\infty = 1.5$ and from 0.5×10^6 to 3.8×10^6 per ft at $M_\infty = 5$. A large vacuum sphere permits operation at the low Reynolds numbers.

Manuscript received March 1963.

Before entering the screen section of the stilling chamber, airflow from the throttling valves is diffused with a series of perforated plates (Fig. 1) in front of a constant diameter stilling chamber equipped with a perforated liner to provide a fairing over three pressure relief port openings. The screens combined should theoretically produce an 8.4 to 1 reduction in turbulence level present upstream of the screens.

During the tests of the hollow cylinder model, the stagnation temperature varied from approximately 80 to 120°F; however, during any one run, the temperature was essentially constant. The absolute humidity of the air from the storage reservoir was approximately 0.00008 lb of water per lb of air (dew point of -40°F at atmospheric pressure).

Sound levels in the stilling chamber of a blowdown tunnel supplied by a high pressure air supply are higher than those in the continuous tunnels primarily because of the noise of the high speed jet flow which issues from the control valve. The total sound power output from the valve at the entrance to the 12-in. tunnel stilling chamber and the corresponding root mean pressure fluctuations are given by the relation shown in Fig. 2.

The present tests were conducted in the 40-Inch Supersonic Tunnel (A) (Fig. 1), which is a continuous, closed circuit, variable density, supersonic wind tunnel with a Mach number range of 1.5 to 6. Variations in Mach number are produced with flexible plates which are automatically positioned at the desired contour by electrically driven jack units.

The 40-in. supersonic tunnel is operated with a central compressor system to provide a Reynolds number range from 0.3×10^6 to 9×10^6 per ft at $M_\infty = 1.5$ and from 0.4×10^6 to 4.3×10^6 per ft at $M_\infty = 6$. Variable densities are obtained at each Mach number by introducing air from the 5,300-ft³, 4000 psia, storage system. Below Mach number 4, the tunnel is operated at stagnation temperatures of approximately 100°F, whereas for tests at the higher Mach numbers, this temperature can be raised up to a maximum of 300°F to prevent test section air liquefaction. Supply air is processed through large capacity, silica-gel driers to maintain an absolute humidity below 0.00001 lb of water per lb of air (dew point of -35°F at atmospheric pressure). Eleven screens combined following an air filter are arranged to theoretically produce a 15 to 1 reduction in turbulence level.

Detailed descriptions of the 12-in. and 40-in. supersonic tunnels are presented in Ref. 3.

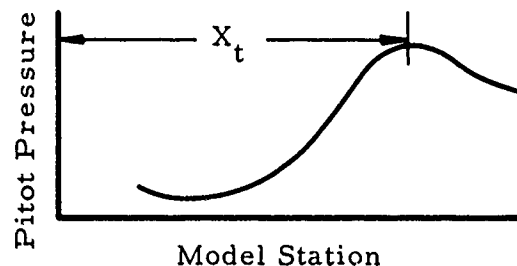
2.2 MODEL AND TEST TECHNIQUE

Extensive tests have been conducted in the 12-in. tunnel on a 3-in. -diam hollow cylinder to study factors which affect boundary-layer transition. The support system of this model was modified to adapt it for use in the 40-in. tunnel.

The model shown in Fig. 3 was constructed of tubular stainless steel which was coated with laminated Fiberglas and an epoxy resin. Polishing the epoxy resin surface produced a surface finish of 10 to 15 microinches rms. Noses with an internal angle of 6 deg and rounded leading edges of 0.003 and 0.008 in. thickness were tested. These noses were used during the earlier tests in the 12-in. tunnel (see Ref. 2).

The variation of the pitot pressure along the model surface was used to detect a point hereafter referred to as the transition location. A single total-head tube (0.02-in. high by 0.04-in. wide) was mounted on a rack which allowed continuous movement of the probe along the surface of the model for a distance of approximately 18 in. to the nose leading edge. A probe providing a reference pressure to the transducer was located diametrically opposite the boundary-layer probe and outside the boundary layer. The transducer was mounted on the probe holder close to the pitot probe to obtain rapid response times.

The transducer and probe position outputs were plotted with an x-y plotter to provide the following trace:



Transition is located by the peak shown on the curve corresponding to a region of relatively high shear stress.

3.0 RESULTS AND DISCUSSION

Before the test results are discussed, it is important to note how the location of transition obtained with the total-head probe compares to the location that would be determined from temperature distribution measurements or schlieren observations. The well-known technique of

moving a pitot probe of small dimensions along a surface provides a transition location corresponding to the beginning of turbulent flow at the end of the transition region. The forward extent of the transition region is defined as the point where the boundary-layer thickness deviates from a laminar rate of growth. From the results presented by Potter and Whitfield (Ref. 2) it may be stated that their schlieren observations provided a transition location which varied from an average of approximately 0.7 to 0.5 of the transition region length for Mach numbers 3 and 5, respectively. In the case of locations obtained from hot wire measurements, which corresponded closely to locations determined from temperature distribution data, the results showed that the variation in transition location was from about 0.6 to 0.8 of the transition length region for Mach numbers 3 and 5, respectively.

To assess the effects of Mach number, unit Reynolds number, and nose bluntness with respect to the results obtained in the 12-in. tunnel, variations that might arise because of techniques and equipment differences were minimized by using the same model, noses, probe, transducer, and readout instrumentation. In addition, the tunnel was operated at the same Mach numbers and Reynolds numbers and at stagnation temperatures which provided a wall temperature ratio near unity. It was hoped that this close correspondence with the tests in the 12-in. tunnel would, for the most part, eliminate some of the variables attendant with experimental studies of boundary-layer transition and thus produce results which would emerge as being predominantly caused by the test unit flow conditions.

The hollow cylinder model with a useable length of 18 in. could not be tested below Mach number 3 because of internal choking and was not tested above Mach number 5 because the transition locations for the unit Reynolds numbers available would exceed 18 in. Transition Reynolds numbers obtained within the framework of these restrictions are presented in Fig. 4 with results from the 12-in. tunnel (Ref. 2). At each Mach number the results for a bluntness of 0.003 in. show that the transition Reynolds numbers in the 40-in. tunnel are significantly higher than those obtained in the 12-in. tunnel; however, the variations with unit Reynolds numbers are essentially the same. It may also be noted that the same conclusions can be drawn for the data obtained at Mach 4 and 5 with a nose bluntness of 0.008 in. To ensure that the nose bluntness between tests had not increased, nose measurements were taken which essentially verified the nose geometry presented in Ref. 2.

The data were sufficient at Mach number 4 to assess the effects of nose bluntness, and cross-plots of these results for constant values of

nose bluntness Reynolds number are presented in Fig. 5. From the procedure used by Potter and Whitfield (Ref. 2), these results are also presented in the form

$$Re_t - (Re_t)_{Re_b \rightarrow 0} = f(Re_b)$$

which results in a single curve since the incremental increase in the transition Reynolds number is essentially independent of unit Reynolds number. Results correlated in this manner and presented in Fig. 6 show that the influence of bluntness is essentially the same in the 12- and 40-in. tunnels.

The effects of Mach number on the magnitude of the transition Reynolds number for two values of unit Reynolds number are shown in Fig. 7. It may be noted that the increase in transition Reynolds number follows closely the trends obtained earlier in the 12-in. tunnel, and, as shown previously, nose bluntness accounts for a large change in transition.

Although the intent of this report is primarily to present transition results obtained in the 40-in. tunnel without attempting to explain the differences in transition Reynolds numbers noted, a review of some of the observations made by investigators studying factors affecting transition may be helpful in eliminating some possible causes of these differences.

Many of the disturbances originating in the stilling chamber (vorticity fluctuations, temperature fluctuations, and sound waves) which have an influence on transition in a supersonic tunnel are minimized or in some cases even canceled by the large velocity ratio available between the stilling chamber and test section at high Mach numbers. It appears that for the Mach number range of the present tests, one can essentially eliminate vorticity in the stilling chamber as a source for free-stream disturbances. For example, Laufer and Marte (Ref. 5) show that no influence of stilling chamber turbulence (vorticity type disturbance) could be detected above $M_\infty = 2.5$. Similar results were obtained by van Driest and Boison (Ref. 6) who found that a Mach number increase diminished the transition promoting influence of supply section turbulence. For example, the strong effect of a nine percent supply turbulence had practically no influence on transition on a 9 deg 51 min cone at Mach number 3.65.

The temperature fluctuations convected along streamlines may also be traceable to conditions in the stilling chamber; however, the influence of these may be minimized by stilling chamber designs incorporating filters, screens, and large contraction ratios. Sound disturbances can

travel along streamlines and may arise from the stilling chamber or from boundaries in the test section, namely, the tunnel wall boundary layer.

As mentioned previously, it was noted by L  ufer that large supply section velocity fluctuations did not influence the transition Reynolds number in the free stream at high Reynolds numbers, and he suggested that the sound-type disturbances in the free stream might originate from the turbulent boundary layer on the tunnel wall (Refs. 5 and 7). Morkovin in Ref. 8 discusses factors which influence free-stream disturbances originating from a sound source.

Hot wire measurements by Schubauer in a turbulent boundary layer on a flat plate and pipe (Ref. 9) showed the presence of a high rate production of turbulence near the wall. Hot wire investigations in the nozzle of the Johns Hopkins University supersonic tunnel (Ref. 8) disclosed within the turbulent boundary layer the presence of a distinct, high intensity, thin turbulent layer. Sound radiated from the boundary layer depends on the distribution of sound sources over the volume where the turbulence is large, and Morkovin (Ref. 8) points out that in addition to this, the sound radiation is strongly amplified by mean shear.

In Ref. 10 a correlation is obtained which shows that pressure fluctuations originating from a supersonic turbulent boundary layer increase with boundary-layer thickness and become independent of Mach number if expressed in terms of boundary-layer displacement thickness. This increase in pressure fluctuations could be produced by an increase in the sound source distribution volume and/or the amplification action of the mean shear as the Reynolds number is decreased and the displacement thickness increased.

The role of the amplification action of the mean shear and the volume of the sound source distribution in the boundary layer has not been specifically defined. As stated by Morkovin (Ref. 8), "if the high-intensity turbulence and the amplifying high mean shear should have more of an effect on sound generation than the total quadrupole volume within the boundary layer, the nozzle region could contribute heavily to the total sound level in the tunnel. Increasing the length of the nozzle expansion would tend to decrease the shear and the local turbulence level while the boundary-layer thickness would grow."

This would imply that if the mean shear were the predominant factor, higher transition Reynolds numbers are to be expected in a larger wind tunnel being operated above about Mach number 3 at the same unit Reynolds number as the smaller tunnel. This cannot be stated as fact since

there may be compensating effects, that is, conditions where the predominance of either the volume of the sound source distribution or mean shear is not universal.

4.0 CONCLUDING REMARKS

From the transition Reynolds number measurements on a hollow cylinder model tested in the von Kármán Gas Dynamics Facility's 12- and 40-in. supersonic wind tunnels at Mach numbers from 3 to 5, it was found that transition Reynolds numbers in the 40-in. tunnel were significantly higher. In addition, it was shown that the influence of nose bluntness was basically the same in both tunnels.

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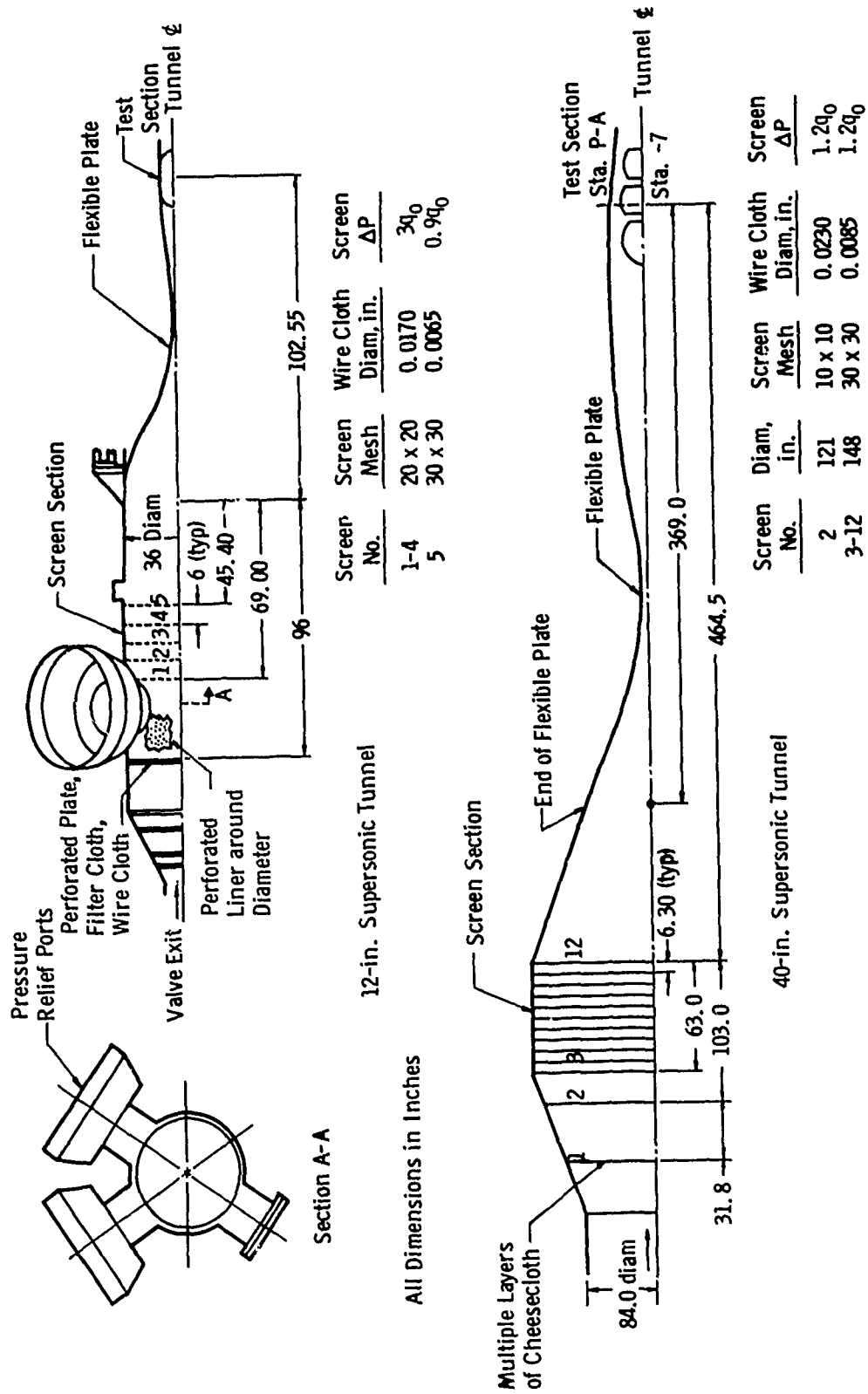


Fig. 1 Tunnel Geometry

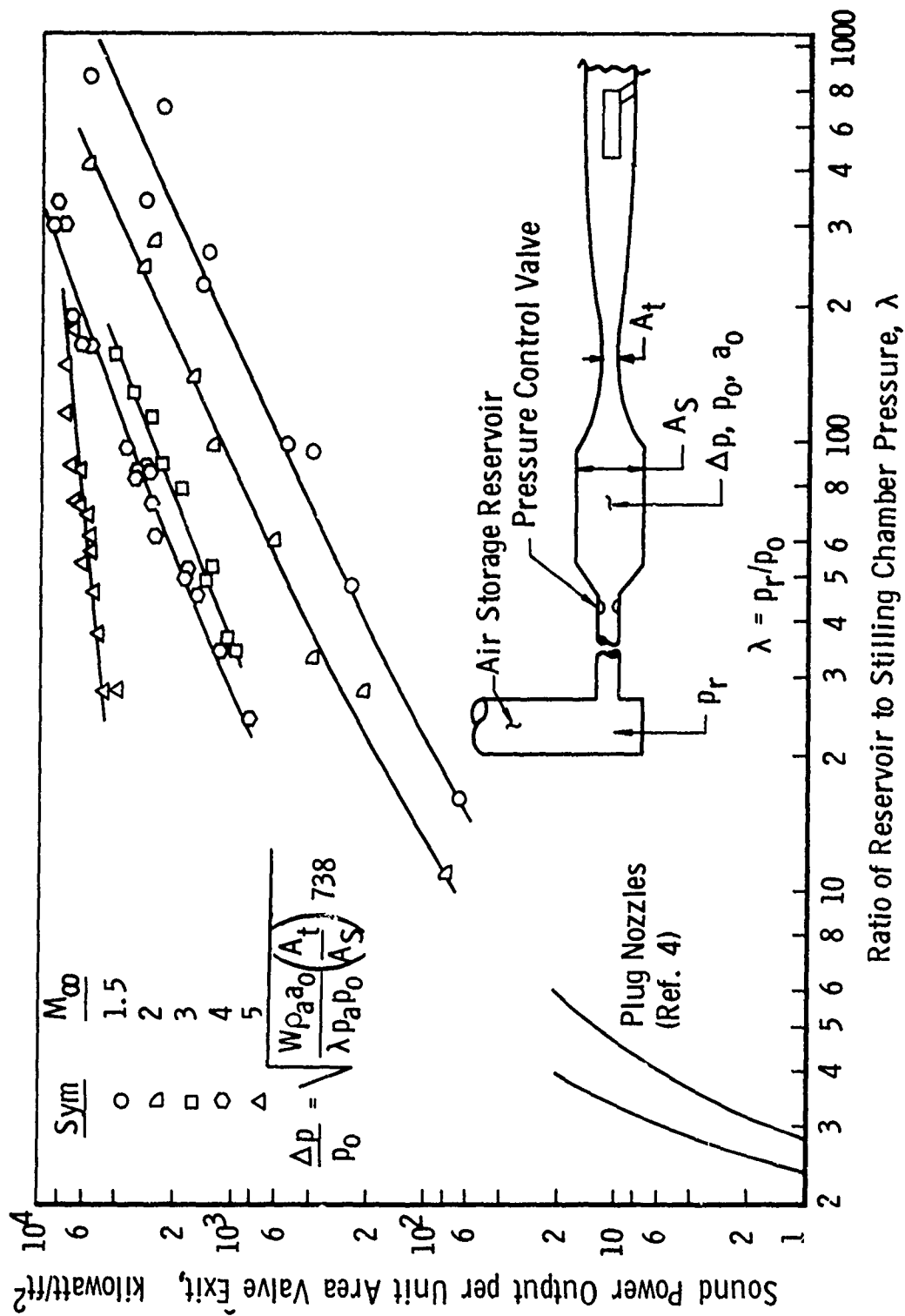


Fig. 2 Valve Sound Power Output, 12-in. Tunnel

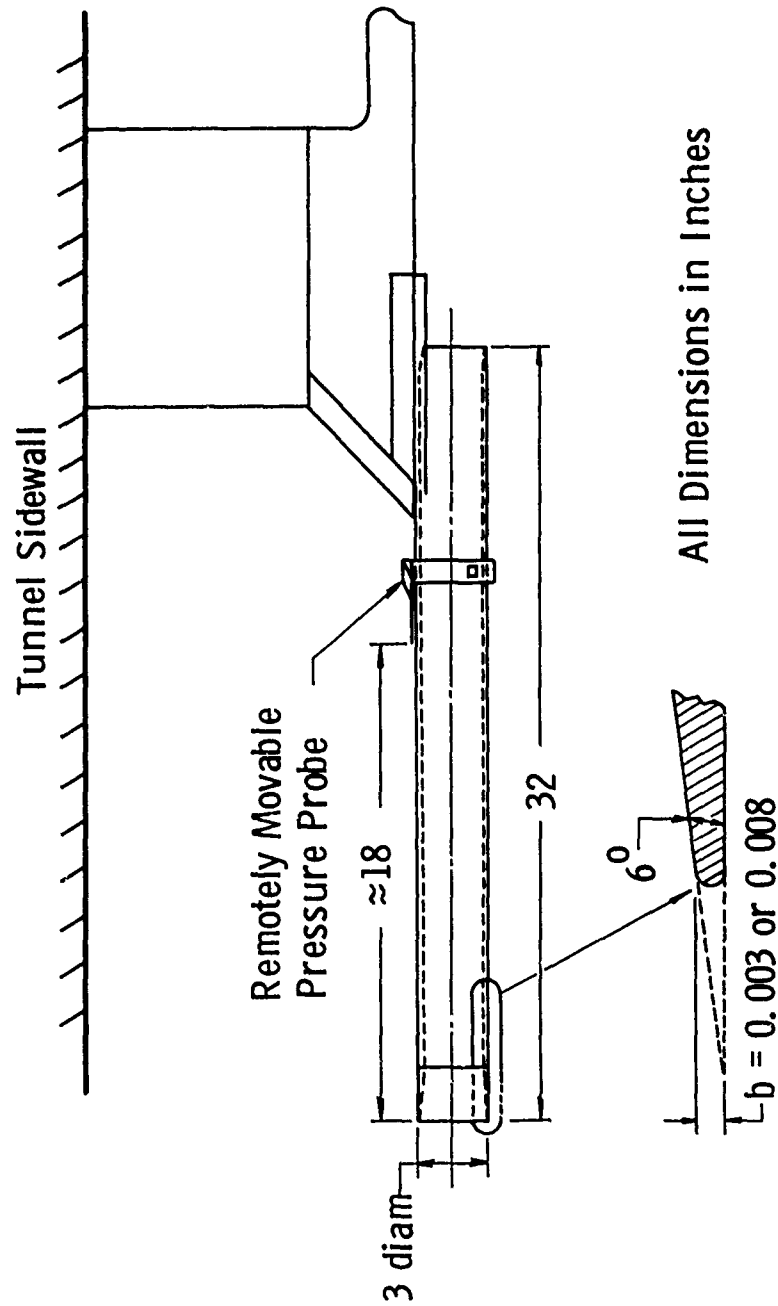


Fig. 3 Transition Model

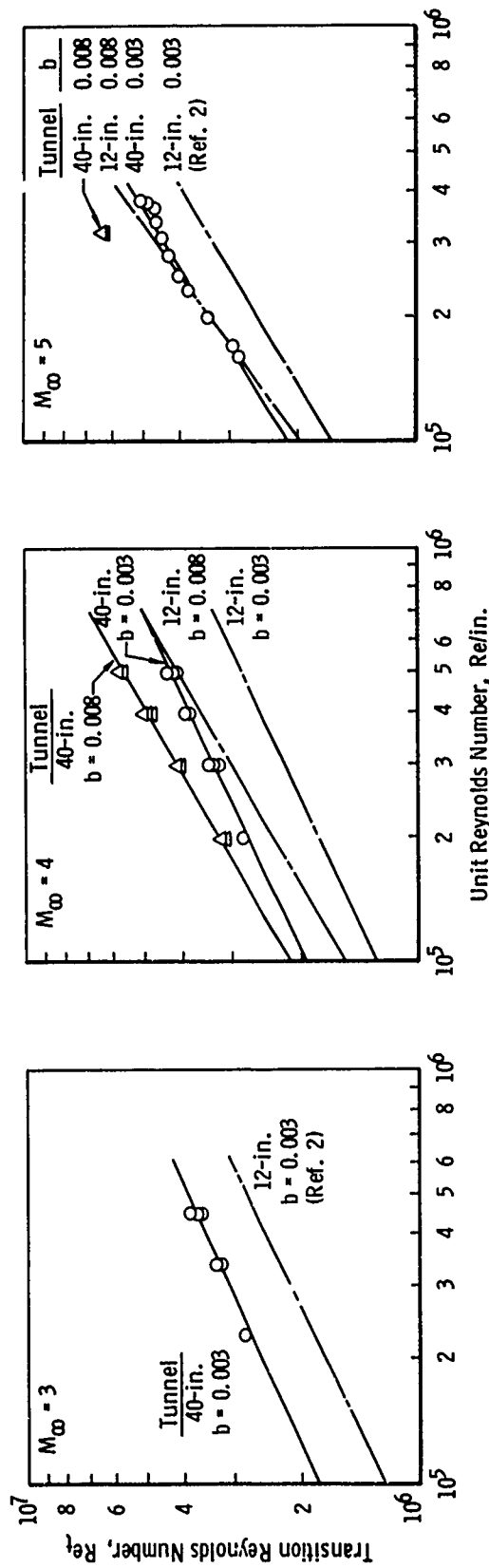


Fig. 4 Transition Reynolds Numbers from 12- and 40-in. Supersonic Tunnels

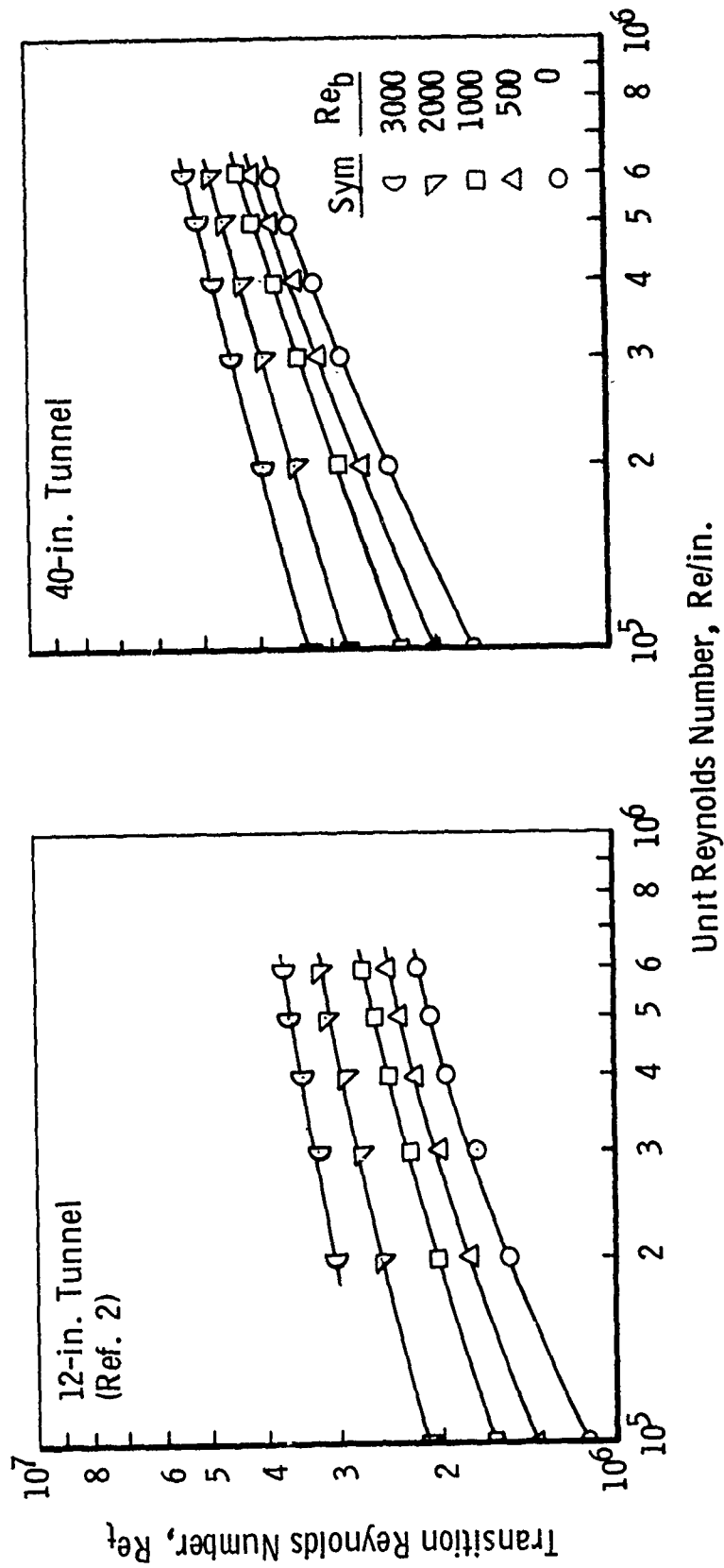


Fig. 5 Influence of Nose Bluntness at Mach Number 4

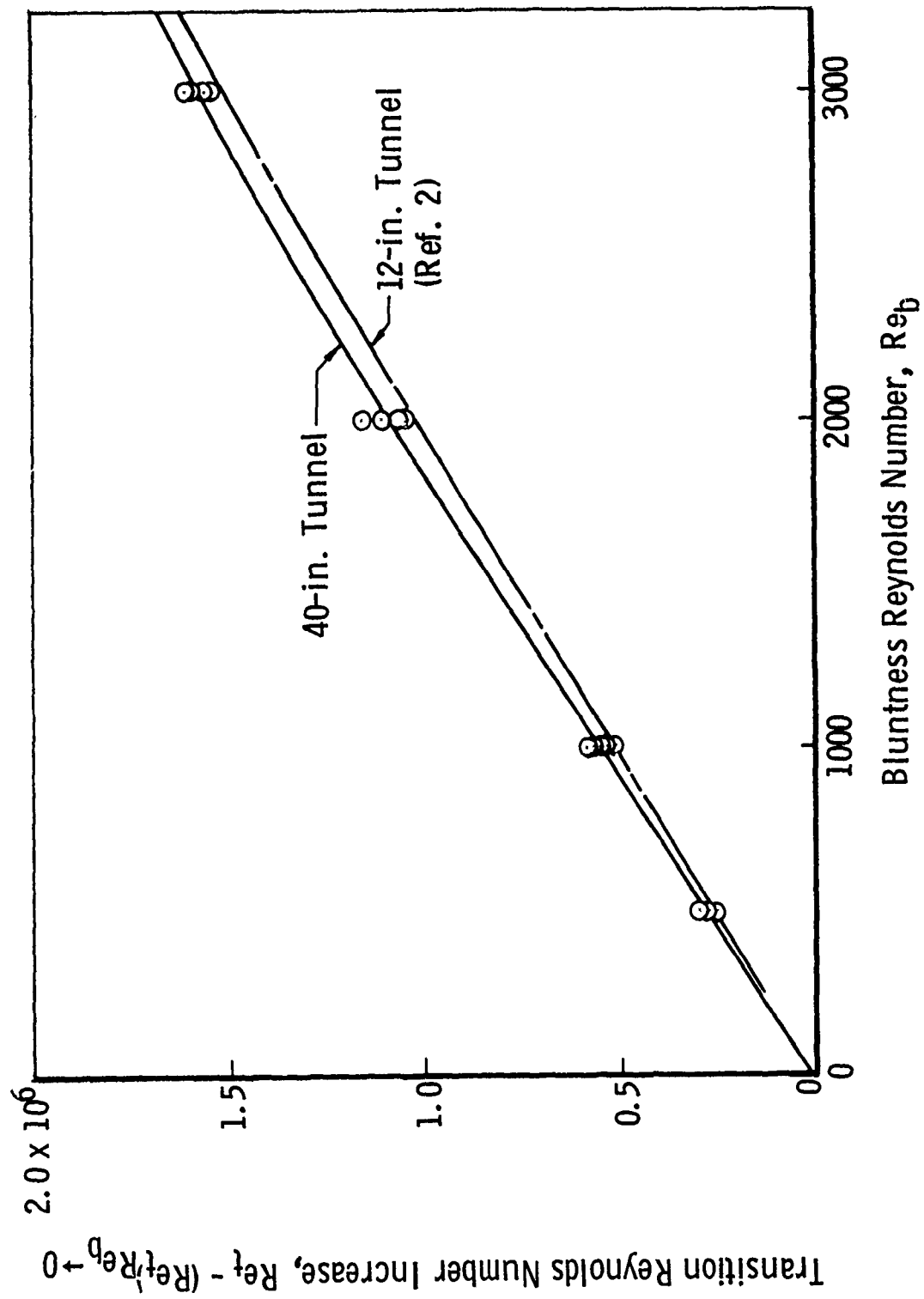


Fig. 6 Comparison of Nose Bluntness Effects in 12- and 40-in. Supersonic Tunnels, $M_\infty = 4$

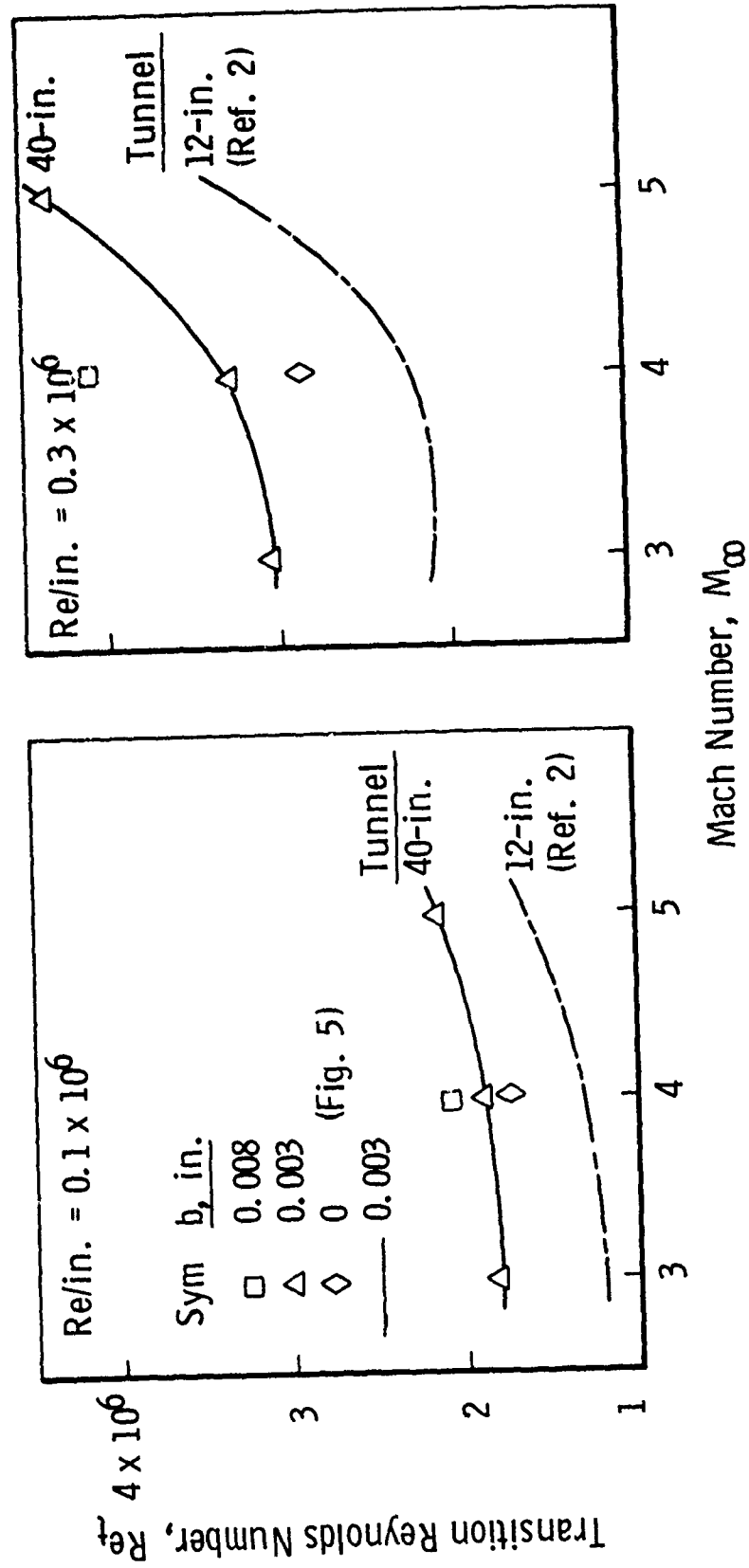


Fig. 7 Variation of Transition Reynolds Number with Mach Number

<p>Arnold Engineering Development Center Arnold Air Force Station, Tennessee Rpt. No. AEDC-TDR-63-57. A COMPARISON OF TRANSITION REYNOLDS NUMBERS FROM 12-IN. AND 40-IN. SUPERSONIC TUNNELS. March 1963, 19 p. incl 10 refs., illus.</p> <p>Unclassified Report</p> <p>Transition Reynolds number measurements on a hollow cylinder in the von Kármán Gas Dynamics Facility's 12-in. and 40-in. supersonic tunnels show that the highest transition Reynolds numbers were obtained in the 40-in. tunnel although the variations with unit Reynolds number were the same at Mach numbers 3 to 5. The influence of nose bluntness in the 40-in. tunnel corresponds closely with the results obtained in the 12-in. tunnel.</p>	<p>1. Supersonic wind tunnels</p> <p>2. Reynolds number</p> <p>I. AFSC Program Area 750A, Project 8952, Task 895202</p> <p>II. Contract AF 40(600)-1000</p> <p>III. ARO, Inc., Arnold AF Sta, Tenn.</p> <p>IV. C. J. Schueler</p> <p>V. Available from OTS</p> <p>VI. In ASTIA Collection</p>	<p>1. Supersonic wind tunnels</p> <p>2. Reynolds number</p> <p>I. AFSC Program Area 750A, Project 8952, Task 895202</p> <p>II. Contract AF 40(600)-1000</p> <p>III. ARO, Inc., Arnold AF Sta, Tenn.</p> <p>IV. C. J. Schueler</p> <p>V. Available from OTS</p> <p>VI. In ASTIA Collection</p>	<p>1. Supersonic wind tunnels</p> <p>2. Reynolds number</p> <p>I. AFSC Program Area 750A, Project 8952, Task 895202</p> <p>II. Contract AF 40(600)-1000</p> <p>III. ARO, Inc., Arnold AF Sta, Tenn.</p> <p>IV. C. J. Schueler</p> <p>V. Available from OTS</p> <p>VI. In ASTIA Collection</p>
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